Response of bare strange stars to energy input onto their surfaces

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ABSTRACT

We study numerically the thermal emission of e^+e^- pairs from a bare strange star heated by energy input onto its surface; heating starts at some moment, and is steady afterwards. The thermal luminosity in e^+e^- pairs increases to some constant value. The rise time and the steady thermal luminosity are evaluated. Both normal and colour superconducting states of strange quark matter are considered. The results are used to test the magnetar model of soft gamma-ray repeaters where the bursting activity is explained by fast decay of superstrong magnetic fields and heating of the strange star surface. It is shown that the rise times observed in typical bursts may be explained in this model only if strange quark matter is a superconductor with an energy gap of more that 1 MeV.

1. Introduction

Strange stars are astronomical compact objects which are entirely made of deconfined quarks (for a review, see Glendenning 1996; Weber 1999). The possible existence of strange stars is a direct consequence of the conjecture that strange quark matter (SQM) may be the absolute ground state of the strong interaction, i.e., absolutely stable with respect to ^{56}Fe (Bodmer 1971; Witten 1984). SQM with a density of $\sim 5 \times 10^{14}$ g cm^{-3} might exist up to the surface of a strange star. Recently, the thermal emission from bare SQM surfaces of strange stars was considered (Usov 1998, 2001a). It was shown that the surface emissivity of SQM in both equilibrium photons and e^+e^- pairs created by the Coulomb barrier at the SQM surface is $\gtrsim 10\%$ of the black body surface emissivity at the surface temperature $T_{\rm s} \gtrsim 1.5 \times 10^9$ K. Below this temperature, $T_{\rm s} < 1.5 \times 10^9$ K, the SQM surface emissivity decreases rapidly with decrease of $T_{\rm s}$.

At the moment of formation of a strange star the surface temperature may be as high as $\sim 10^{11}$ K (e.g., Haensel, Paczyński, & Amsterdamski 1991). Since SQM at the surface of a bare strange star is bound via strong interaction rather than gravity, such a star can radiate at the luminosity greatly exceeding the Eddington limit, up to $\sim 10^{52}$ ergs s^{-1} at $T_{\rm s} \sim 10^{11}$ K. (Alcock, Farhi, & Olinto 1986; Chmaj, Haensel, & Slomiński 1991; Usov 1998, 2001a). A young strange star cools rapidly, and within about a month after its formation the surface temperature is less than 2.5×10^8 K (e.g., Pizzochero 1991). In this case, the thermal luminosity from the stellar surface in both equilibrium photons and e^+e^- pairs is negligibly small, $L_{\rm th} < 10^{25}$ ergs s^{-1}. A bare strange star with such a low surface temperature may be a strong source of radiation only if its surface is reheated. Recently, response of a bare strange star to accretion of a massive comet-like object with the mass $\Delta M \sim 10^{25}$ g onto the stellar surface was considered (Usov 2001b). It was shown that the light curves of the two giant bursts observed from the soft γ-ray repeaters SGR 0526-66 and SGR 1900+14 may be easily explained in this model.

In this paper we report on our numerical simulations of the response of a bare strange star to energy input onto its surface. We consider a wide range of the rate of the energy input. Both normal and colour superconducting SQM are discussed.

2. Formulation of the problem

The model to be studied is the following. The energy input onto the surface of a bare strange star starts at the moment $t = 0$, and it is spherical and steady at $t \geq 0$. Since in our simulations the surface temperature is not higher than a few $\times 10^9$ K, e^+e^- pairs created by the Coulomb barrier are the main component of the thermal emission from the stellar surface (Usov 2001a). We assume that the process of the energy input has no effect on the outflow of both created pairs and photons which form due to annihilation of some of these

pairs (cf. Usov 2001b).

The equation of heat transfer that describes the temperature distribution at the surface layers of a strange star is

$$C\frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(K\frac{\partial T}{\partial x}\right) - \varepsilon_\nu\,, \tag{1}$$

where C is the specific heat for SQM per unit volume, K is the thermal conductivity, and ε_ν is the neutrino emissivity.

The heat flux due to thermal conductivity is

$$q = -K dT/dx\,. \tag{2}$$

At the stellar surface, $x = 0$, the heat flux directed into the strange star is equal to (Usov 2001b)

$$q = L_{\rm input}/(4\pi R^2) - \varepsilon_\pm f_\pm\,, \tag{3}$$

where $L_{\rm input}$ is the rate of the energy input onto the stellar surface, $R \simeq 10^6$ cm is the radius of the star, $\varepsilon_\pm f_\pm$ is the energy flux in e^+e^- pairs emitted from the SQM surface, $\varepsilon_\pm \simeq m_ec^2 + kT_{\rm s}$ is the mean energy of created pairs,

$$f_\pm \simeq 10^{39.2}\, T_{\rm s,9}^3 \exp\left(-\frac{11.9}{T_{\rm s,9}}\right) J(\zeta)\ \ {\rm cm}^{-2}\,{\rm s}^{-1} \tag{4}$$

is the flux of pairs from the unit SQM surface,

$$J(\zeta) = \frac{1}{3}\frac{\zeta^3 \ln{(1+2\zeta^{-1})}}{(1+0.074\zeta)^3} + \frac{\pi^5}{6}\frac{\zeta^4}{(13.9+\zeta)^4}\,, \tag{5}$$

$\zeta \simeq (2 \times 10^{10}\ \mathrm{K})/T_{\rm s}$, and $T_{\rm s,9}$ is the surface temperature in units of 10^9 K.

Eqs. (2) – (5) give a boundary condition on dT/dx at the stellar surface. We assume that at the initial moment, $t = 0$, the temperature in the surface layers is constant, $T = 10^8$ K.

It has been suggested (Bailin & Love 1979, 1984) that the quarks may eventually form Cooper pairs. Recently, superconductivity of SQM was considered in detail (for a review, see Rajagopal, & Wilczek 2000; Alford, Bowers, & Rajagopal 2001), and it was shown that SQM is plausibly a colour superconductor if its temperature not too high. Below, we consider both normal and superconducting SQM.

2.1. The Normal State of SQM

For non-superconducting SQM, the contribution of the quarks to both the specific heat and the thermal conductivity prevails over the contributions of the electrons, photons and gluons. In this case we have (Iwamoto 1982; Heiselberg & Pethick 1993; Benvenuto & Althaus 1996)

$$C \simeq C_q \simeq 2.5 \times 10^{20} (n_b/n_0)^{2/3} T_9 \ \ \mathrm{ergs\ cm^{-3}\ K^{-1}} \tag{6}$$

$$K \simeq K_q \simeq 6 \times 10^{20} \alpha_c^{-1} (n_b/n_0)^{2/3} \ \ \mathrm{ergs\ cm^{-1}\ s^{-1}\ K^{-1}} \tag{7}$$

$$\varepsilon_\nu \simeq 2.2 \times 10^{26} \alpha_c Y_e^{1/3} (n_b/n_0) T_9^6 \ \ \mathrm{ergs\ cm^{-3}\ s^{-1}} \tag{8}$$

where $n_0 \simeq 1.7 \times 10^{38}$ cm^{-3} is normal nuclear matter density, n_b is the baryon number density of SQM, $\alpha_c = g^2/4\pi$ is the QCD fine structure constant, g is the quark-gluon

coupling constant, $Y_e = n_e/n_b$ is the number of electrons per baryon, and T_9 is the temperature in units of 10^9 K.

2.2. The Colour Superconducting State of SQM

SQM may be a colour superconductor if its temperature is below some critical value. In the classic model of Bardeen, Cooper, and Schrieffer the critical temperature is $T_c \simeq 0.57\Delta_0/k_{\rm B}$, where Δ_0 is the energy gap at zero temperature and $k_{\rm B}$ is the Boltzmann constant (e.g., Carter & Reddy 2000). The value of Δ_0 is very uncertain and lies in the range from $\sim 0.1 - 1$ MeV (Bailin & Love 1984) to $\sim 50 - 10^2$ MeV (Alford, Rajagopal, & Wilczek 1998; Alford, Berges, & Rajagopal 1999; Pisarski & Rischke 2000).

We use the following interpolation formula for the temperature dependence of the energy gap(e.g., Carter & Reddy 2000):

$$\Delta(T) = \Delta_0 \left[1 - \left(\frac{T}{T_c}\right)^2\right]^{1/2}. \tag{9}$$

Superconductivity modifies the properties of SQM significantly. The specific heat of superconducting SQM increases discontinuously as the temperature falls below the critical temperature, and then decreases exponentially at lower temperatures. For the quark specific heat at $T \leq T_c$ we adopt the theoretical results of Mühlschlegel (1959) for superconducting nucleons, i.e., (Horvath, Benvenuto, & Vucetich 1991; Blaschke, Klähn, & Voskresensky 2000)

$$\tilde{C}_q = 3.2 C_q (T_c/T) \exp\left(-\Delta_0/T\right)$$

$$\times[2.5 - 1.7T/T_c + 3.6(T/T_c)^2]\,, \tag{10}$$

here and below tilde signifies that this value relates to superconducting SQM. Even at $T \ll T_c$ the suppression of the specific heat of SQM is never complete because the electrons remain unpaired. The specific heat of superconducting SQM which is used in our simulations is $\tilde{C} \simeq \tilde{C}_q + C_e$, where

$$C_e \simeq 5.7 \times 10^{19} Y_e^{2/3} (n_b/n_0)^{2/3} T_9 \ \text{ergs cm}^{-3}\ \text{K}^{-1}\,, \tag{11}$$

is the specific heat of the electron subsystem of SQM (Blaschke, Grigorian, & Voskresensky 2001).

At $T < T_c$ both the thermal conductivity of SQM and its neutrino emissivity are suppressed by a factor of $\exp\left(-\Delta/k_{\rm B}T\right)$. In our simulations, we adopt

$$\tilde{K} = K_q \exp[-\Delta(T)/k_{\rm B}T] + K_e\,, \tag{12}$$

$$\tilde{\varepsilon}_\nu = \varepsilon_\nu \exp[-\Delta(T)/k_{\rm B}T]\,, \tag{13}$$

where K_q and ε_ν are given by equations (7) and (8), respectively, and

$$K_e \simeq 5.5 \times 10^{23} Y_e (n_b/n_0) T_9^{-1} \ \text{ergs cm}^{-1}\ \text{s}^{-1}\ \text{K}^{-1} \tag{14}$$

is the thermal conductivity of the electrons (e.g., Blaschke et al. 2001)

3. Results of numerical simulations

The set of equations (1) – (5) was solved numerically for both normal ($\Delta_0 = 0$) and superconducting ($\Delta_0 > 0$) states of SQM. We assumed the typical values of $\alpha_c = 0.1$, $n_b = 2n_0$, and $Y_e = 10^{-4}$. Figure 1 shows a typical temporal behaviour of the strange star luminosity, $L_\pm = 4\pi R^2 \varepsilon_\pm f_\pm$, in e^+e^- pairs. From this Figure, we can see that $L_\pm$ increases eventually to its maximum value $L_\pm^{\rm max}$. The rate of this increase may be characterized by the rise time $\tau_\pm$ that is determined as a time interval from the initial moment, $t = 0$, to the moment when $L_\pm$ is equal to $(1/2)L_\pm^{\rm max}$. The results of our simulations are presented in Tables 1 and 2. There is a critical value, $L_{\rm cr}$, of the input luminosity at which the dependence of $L_\pm^{\rm max}$ on $L_{\rm input}$ changes qualitatively (see Table 1). $L_{\rm cr}$ is $\sim 10^{40}$ ergs s^{-1} for normal SQM and $\sim 3 \times 10^{38}$ ergs s^{-1} for superconducting SQM with $\Delta_0 \gtrsim 0.3$ MeV. At $L_{\rm input} \gtrsim$ a few $\times\, L_{\rm cr}$, $L_\pm^{\rm max}$ is about $L_{\rm input}$ while when $L_{\rm input}$ is a few times below than $L_{\rm cr}$ the thermal emission of e^+e^- pairs from the stellar surface is negligible.

In our simulations, the rise time $\tau_\pm$ varies in a very wide range from $\sim 10^6$ s at $L_{\rm input} \lesssim 10^{40}$ ergs s^{-1} and $\Delta_0 \lesssim 0.1$ MeV to $\sim 10^{-8}$ s at $L_{\rm input} \sim 10^{45}$ ergs s^{-1} and $\Delta_0 \gtrsim 1$ MeV (see Table 2).

At $\Delta_0 \gtrsim 1$ MeV the thermal emission of e^+e^- pairs does not depend on Δ_0 because in this case both the specific heat of the quarks and their thermal conductivity are strongly suppressed, and the heat transport is mostly determined by the electron subsystem of SQM.

The rise time of the luminosity in neutrinos is many orders of magnitude larger that $\tau_\pm$, especially when $\tau_\pm$ is small. In our model the neutrino luminosity may increase up to $L_{\rm input} - L_\pm^{\rm max}$ when t goes to infinity. This is because all energy which is delivered onto the stellar surface is radiated either from the surface by e^+e^- pairs or from the stellar interior by neutrinos.

4. Discussion

Since bare strange stars can radiate at the luminosities greatly exceeding the Eddington limit (Alcock et al. 1986; Chmaj et al. 1991; Usov 1998, 2001a), these stars are reasonable candidates for soft γ-ray repeaters (SGRs) that are the sources of brief ($\sim 10^{-2} - 10^{2}$ s) bursts with Super-Eddington luminosities, up to $\sim 10^{43} - 10^{45}$ ergs s^{-1}. The bursting activity of a SGR may be explained by fast heating of the bare, rather cold ($T_{\rm s} \lesssim 10^8$ K) surface of a strange star up to the temperature of $\sim (1-2)\times 10^9$ K and its subsequent thermal emission (Usov 2001a). The heating mechanism may be either fast decay of superstrong ($\sim 10^{14} - 10^{15}$ G) magnetic fields (Usov 1984; Duncan & Thompson 1992; Paczyński 1992; Thompson & Duncan 1995; Cheng & Dai 1998; Heyl & Kulkarni 1998) or impacts of comet-like objects onto the stellar surface (Harwitt & Salpeter 1973; Newman & Cox 1980; Zhang, Xu, & Qiao 2000; Usov 2001b). The magnetar model of SGRs which is based on the first mechanism is most popular now. In this model, the magnetic energy of a strongly magnetized strange star (magnetar) may be released from time to time due to MHD instabilities. A violent release of energy inside a magnetar excites surface oscillations (e.g., Thompson & Duncan 1995). In turn, this shaking may generate strong electric fields in the magnetar magnetosphere which accelerate particles to high energies. These high energy particles bombard the surface of the strange star and heat it. At the input luminosities of $\sim 10^{41} - 10^{45}$ ergs s^{-1}, which are typical for SGRs, the efficiency of reradiation of the partical energy by the stellar surface to e^+e^- pairs is very high, $L_\pm/L_{\rm input} \simeq 1$, especially for superconducting SQM (see Table 1). Since for SGRs the burst luminosities are at least a few orders of magnitude higher than $L_* \simeq 4\pi m_{\rm e}c^3R/\sigma_{\rm T} \simeq 10^{36}$ ergs s^{-1}, the outflowing e^+e^- pairs mostly annihilate in the vicinity of the strange star (e.g., Beloborodov 1999). Therefore, at $L_{\rm input} \sim 10^{41} - 10^{45}$ ergs s^{-1} far from the star the luminosity in X-ray and γ-ray photons practically coincides with $L_{\rm input}$, $L_\gamma \simeq L_\pm - L_* \simeq L_\pm \simeq L_{\rm input}$.

Two giant bursts were observed on 5 March 1979 and 27 August 1998 from SGR $0526-66$ and SGR $1900+14$, respectively. The peak luminosities of these bursts were $\sim 10^{45}$ ergs s^{-1} (Fenimore, Klebesadel, & Laros 1996; Hurley et al. 1999). In this case, from Table 2 the rise time expected in our model is $\lesssim 10^{-3}$ s that is consistent with available data on the two giant bursts (Mazets et al. 1999). This is valid irrespective of that SQM is a colour superconductor or not. For typical bursts of SGRs the luminosities are $\sim 10^{41} - 10^{42}$ ergs s^{-1} (e.g., Kouveliotou 1995), and the observed rise times ($\sim 10^{-1} - 10^{-3}$ s) may be explained in our model only if SQM is a superconductor with the energy gap $\Delta_0 \gtrsim 1$ MeV (see Table 2).

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Table 1: The maximum luminosity $L_{\pm}^{\max}$ in $e^{+}e^{-}$ pairs

$L_{\rm input}$,	The energy gap Δ, MeV				
ergs $\rm s^{-1}$	0	0.1	0.3	1	10
10^{38}	$< 10^{15}$	$< 10^{15}$	$\sim 10^{25}$	$\sim 10^{25}$	$\sim 10^{25}$
3×10^{38}	$< 10^{15}$	3×10^{33}	9.6×10^{37}	9.9×10^{37}	10^{38}
10^{39}	$\sim 10^{17}$	2×10^{36}	6.8×10^{38}	7.2×10^{38}	7.3×10^{38}
3×10^{39}	10^{31}	8×10^{38}	2.67×10^{39}	2.72×10^{39}	2.72×10^{39}
10^{40}	1.1×10^{39}	4.7×10^{39}	9.6×10^{39}	9.7×10^{39}	9.7×10^{39}
10^{41}	8.4×10^{40}	8.5×10^{40}	9.93×10^{40}	9.96×10^{40}	9.96×10^{40}
10^{42}	9.76×10^{41}	9.79×10^{41}	9.991×10^{41}	9.996×10^{41}	9.996×10^{41}
10^{43}	9.96×10^{42}	9.96×10^{42}	9.998×10^{42}	10^{43}	10^{43}
10^{44}	9.992×10^{43}	9.992×10^{43}	9.999×10^{43}	10^{44}	10^{44}
10^{45}	9.999×10^{44}	9.999×10^{44}	10^{45}	10^{45}	10^{45}

Note. — Units of $L_{\pm}^{\max}$ are ergs $\rm s^{-1}$. In all cases when in this Table $L_{\pm}^{\max}$ is equal to $L_{\rm input}$ we have $(L_{\rm input} - L_{\pm}^{\max})/L_{\rm input} < 10^{-4}$.

Table 2: The rise time $\tau_{\pm}$ for the thermal emission of $e^{+}e^{-}$ pairs

$L_{\rm input}$, ergs s^{-1}	The energy gap Δ, MeV				
	0	0.1	0.3	1	10
10^{38}	$\sim 10^{6}$	$\sim 10^{6}$	10^{4}	10^{4}	10^{4}
3×10^{38}	$\sim 10^{6}$	1.2×10^{6}	2×10^{4}	6×10^{3}	6×10^{3}
10^{39}	6×10^{5}	10^{6}	3.6×10^{3}	7.6×10^{2}	7.7×10^{2}
3×10^{39}	9×10^{5}	6×10^{5}	9×10^{2}	1.2×10^{2}	1.2×10^{2}
10^{40}	4.4×10^{5}	3.4×10^{4}	1.5×10^{2}	13.5	13.5
10^{41}	1.3×10^{4}	3.5×10^{3}	4.8	0.19	0.19
10^{42}	2.4×10^{2}	1.5×10^{2}	0.18	2.5×10^{-3}	2.5×10^{-3}
10^{43}	3.9	2.5	9×10^{-3}	3.6×10^{-5}	3.6×10^{-5}
10^{44}	6.7×10^{-2}	5.6×10^{-2}	5.5×10^{-4}	5.6×10^{-7}	5.6×10^{-7}
10^{45}	1.3×10^{-3}	1.2×10^{-3}	4.6×10^{-5}	1.3×10^{-8}	0.8×10^{-8}

Note. — Units of $\tau_{\pm}$ are seconds.

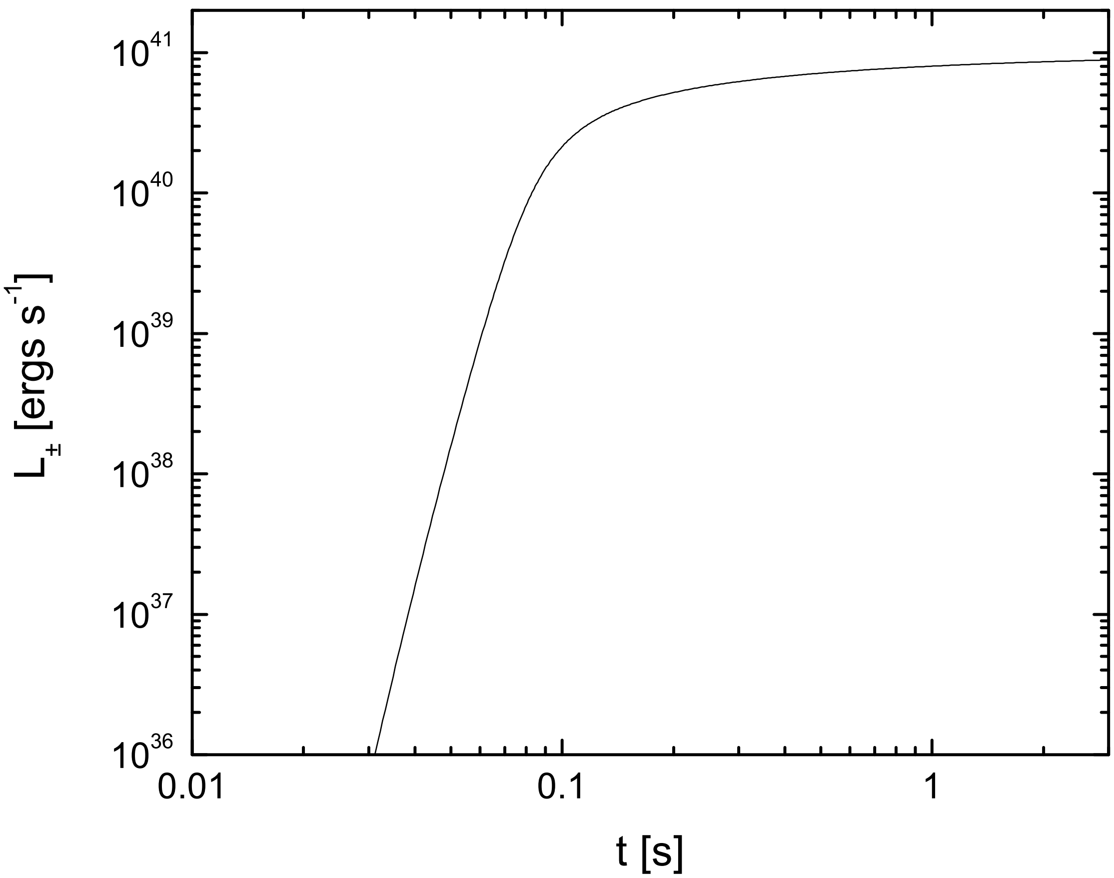

Fig. 1.— The thermal luminosity in e^+e^- pairs as a function of time for $L_{\rm input} = 10^{41}$ ergs s^{-1} and $\Delta_0 = 1$ MeV.